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RELATIONSHIP BETWEEN BACKSCATTERING AND BEAM SCATTERING COEFFICIENTS DERIVED FROM NEW MEASUREMENTS OF LIGHT SCATTERING PHASE FUNCTIONS

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INTRODUCTION

Processing of optical remote sensing information requires a knowledge of dependence between backscattering and beam scattering coefficients. Until recently this dependency was primarily derived from fifteen angular scattering coefficients measured more than 30 years ago by Petzold [1]. A few years ago a new probe to measure an angular scattering coefficient of natural waters was developed and built by the Marine Hydrophysical Institute in Sevastopol, Crimea [2]. Since 2000 his device was employed in several LEO-15 expeditions near the coast of New Jersey, and in May 2002 expedition in the northern Gulf of Mexico.

The results of these measurements show that coastal waters can be divided into two distinct types: one - similar to the waters of Petzold experiment near the California coast, and the other - biologically more pure type [3] that was experimentally detected during LEO-15 experiment in 2001. This presentation analyzes more than 875 angular scattering coefficients measured in different areas of World Ocean (873) and Lake Baykal (2). The main difference between Petzold-type coastal waters and biologically pure waters is characterized by the dependence between backscattering and beam scattering coefficients [3, 4]. The backscattering probability, or ratio of these coefficients, for the biologically pure coastal waters is about three times smaller than the backscattering probability for the Petzold-type waters. This result is very important for algorithms to process optical information measured from satellites and aircrafts and modeling light propagation in water.

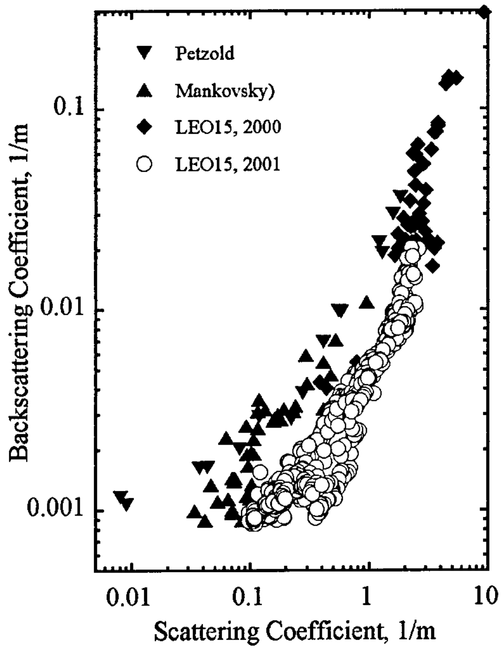

Fig. 1. Backscattering coefficient b_B as a function of scattering coefficient b.

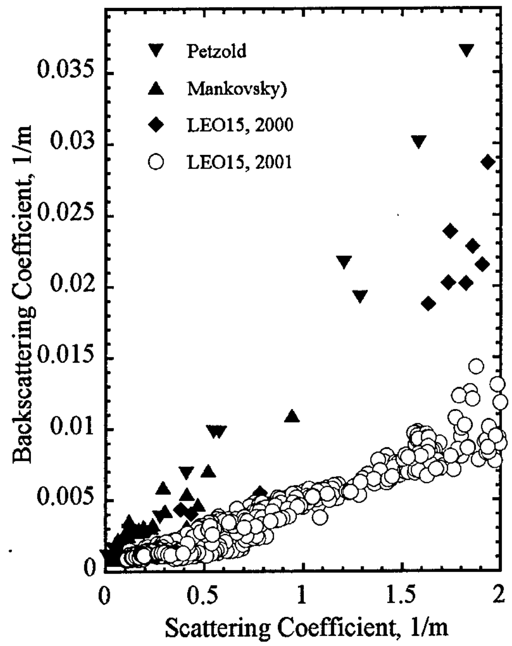

Fig. 2. Lower left corner of Fig. 1 plotted in linear scales

Here we discuss the relationships between backscattering b_B and scattering b coefficients of the following four sets of 875 phase functions: 1) Fifteen (15) Petzold phase functions [1] measured at 515 nm in California Bay; 2) Forty one (41) Mankovsky phase functions [5-7] measured at 520 nm in Atlantic, Indian, and Southern oceans, Mediterranean and Black seas, and Lake Baykal in Siberia. 3) Sixty (60) high resolution phase functions measured at 555 nm near the shores of New Jersey during the LEO-15 experiment in 2000; and, 4) Seven hundred and fifty nine (759) high resolution phase functions measured at 555 nm near the shores of New Jersey during the LEO-15 experiment in 2001 [8]. The tables of the phase functions with the corresponding values of b_B, b, and beam attenuation coefficient c for the first two sets of data are published in Refs. [1] and [5, 6] respectively. The table for b and b_B measured during the LEO-15 experiment in 2000 is given in the Appendix to this paper.

RELATIONSHIP BETWEEN BACKSCATTERING AND SCATTERING COEFFICIENTS

Figures 1 and 2 show relationship between b_B and b for all four sets of data in log-log and linear scales. The data displayed in Figures 1 and 2 from the backscattering point of view clearly represent two distinct optical water types. The first water type (we name it Petzold-type water, or P-type water) includes all Petzold measurements, most of the Mankovsky and a majority of LEO-15 2000 measurements. The second type of water is represented by the bulk of the LEO-15 2001 measurements, small part of the LEO-15 2000 measurements, and some of the Mankovsky data. This type ideally represents the

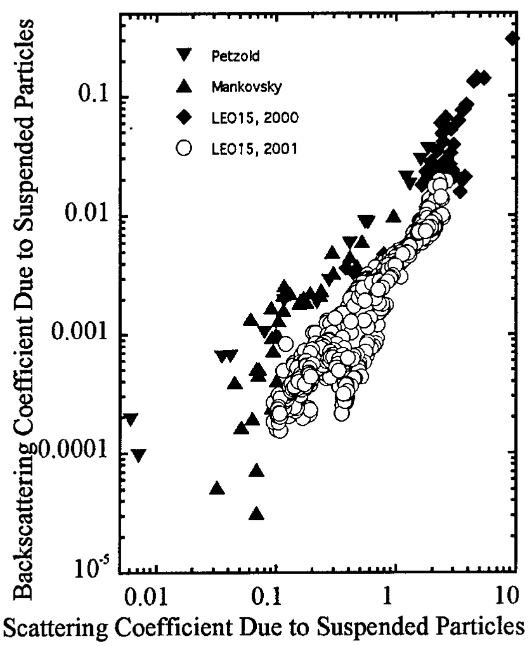

Fig. 3. ***Backscattering coefficient due to suspended particles (SP) versus scattering coefficient due to SP.***

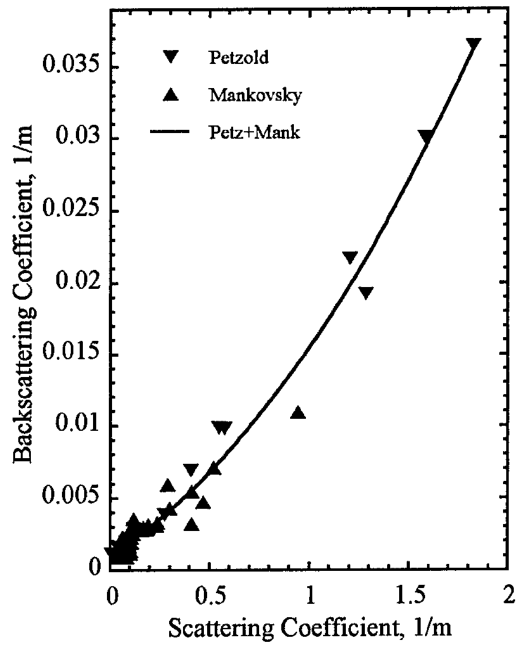

Fig. 4. ***Backscattering coefficient b_B as a function of scattering coefficient b for Petzold and Mankovsky PHFs.***

optical model proposed in Ref. [3] with the modeling algorithm and code published in [4]. According to Ref. [3] we name it a Biologically Stable water type (BS-type water). The BS- type water is modeled as a mixture of terrigenic particles (with the sizes between 0.01 and 1.3 mkm), and biogenic (phytoplankton) particles (with the sizes between 1.3 and 13 mkm) [3, 9]. The model proposed in [3, 4] restores all inherent optical properties of the second, BS- type water, from the value of one property at certain wavelength.

The P-type water differs from the BS-type water by the ratio of backscattering to scattering coefficients, $B = b_B/b$. The ratio B has a physical meaning of the probability of backscattering. The value of B for the P-type water is approximately three times larger than the value of B for the BS-type water. It means that the Petzold-type waters contain larger fraction of small particles than the Biologically Stable waters. It also means that it is possible to expand seawater optical model [3] to include P-type waters and waters intermediate between P- and BS-types.

Figure 3 shows the same values of b_B and b as displayed in Fig. 1. The difference consists only in a removal of pure water components of b_B and b. The comparison between Fig.1 and Fig.3 shows that the pure water correction will significantly influence only 4-5 measurements by Mankovsky. It means that the statistics of resulting equations will change negligently, but the complexity of equations will increase significantly. This explains why we omitted a pure water correction procedure in our derivation of the subsequent equations.

For the purposes of modeling optical remote sensing, visibility, and laser propagation in seawater it is convenient to have empirical relationships between b_B and b. Our exten-

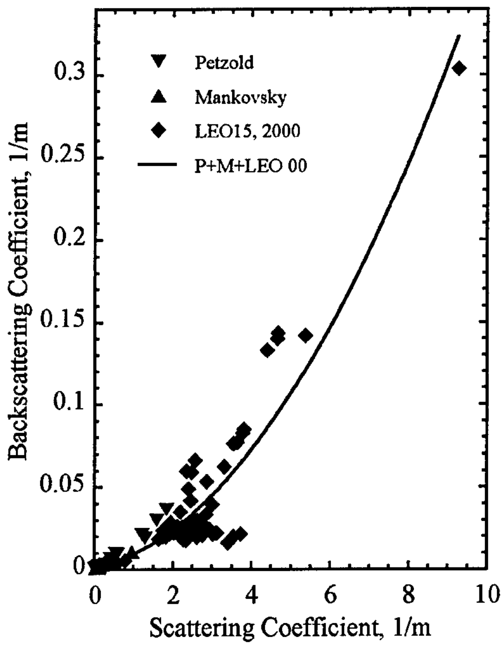

Fig. 5. ***The same as Fig. 2 only with the addition of LEO-15 (2000) PHFs measured near New Jersey coast.***

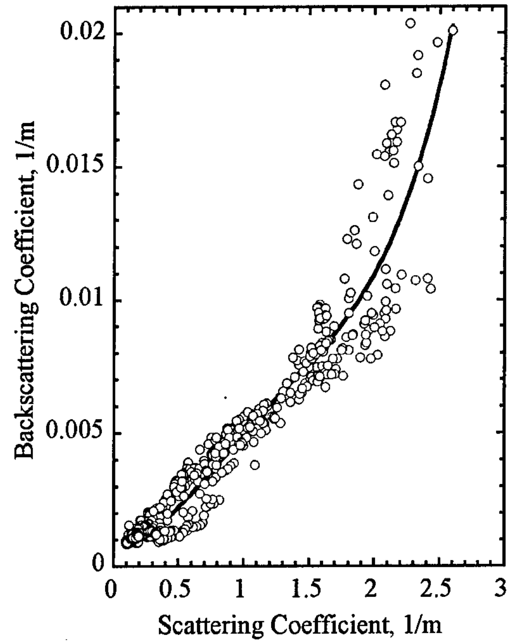

Fig. 6. ***Backscattering coefficient as a function of scattering coefficient for the LEO-15 (2001) PHFs.***

sive set of data allows us to obtain the following three dependencies for several combination of measurements.

Figure 4 shows that both Petzold and Mankovsky measurements fall in the same category of P-type waters. The relationship obtained from 56 Petzold and Mankovsky phase functions can be expressed as follows:

$$b_B = 0.001095 + 0.0083274\,b + 0.0059797\,b^2,\quad r^2 = 0.97877,\quad 0.002\,\mathrm{m}^{-1} \le b \le 2\,\mathrm{m}^{-1}. \tag{1}$$

The LEO-15 measurements also give very good examples of P-type waters. Together with the Petzold and Mankovsky measurements they are shown in Fig. 5. The regression based on this figure that covers the range of b's up to 10 1/m has the following form:

$$b_B = 0.0012002 + 0.005058\,b + 0.0032065\,b^2,\quad r^2 = 0.87362,\quad 0.002\,\mathrm{m}^{-1} \le b \le 10\,\mathrm{m}^{-1}. \tag{2}$$

The relationship between b_B and b for BS-type waters is shown in Fig. 6. The dependence is nonlinear and may be expressed as a polynomial of the 4-th order:

$$\begin{aligned} b_B &= 0.0010313 - 0.0013315\,b + 0.010479\,b^2 \\ &\quad - 0.0067754\,b^3 + 0.0015573\,b^4,\quad r^2 = 0.92057,\quad 0.002\,\mathrm{m}^{-1} \le b \le 2.6\,\mathrm{m}^{-1}. \end{aligned} \tag{3}$$

We proposed here three new empirical regressional equations that express b_B through the values of b. Equations (1) and (2) are derived for the Petzold-type waters. For relatively clear P-type waters with $b < 2$ 1/m Eq. (1) is applicable. For more turbid ($b \ge 2$ 1/m) P-type waters Eq. (2) gives better results. For clear biologically stable waters Eq. (3) is valid and is supported by the optical model proposed in Ref. [3].

CONCLUSION

A set of three new regression relationships that couples backscattering coefficient to scattering coefficient of marine (and lake) waters is proposed. This set of equations is valid in the range of variability of scattering coefficient between 0.002 and 10 1/m and is based on experimental measurements of 875 phase functions of scattering in such diverse areas as Atlantic, Pacific, Indian and Southern oceans, Mediterranean and Black seas, and lake Baykal. These regressions could be used for processing remotely measured optical information, and modeling visibility and laser propagation in natural waters.

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APPENDIX: ***Table of scattering and backscattering coefficients measured during the LEO-15 experiment near a New Jersey Atlantic coast in 2000 (wavelength of light 555 nm).***

b, 1/m	b_B , 1/m	b, 1/m	b_B , 1/m	b, 1/m	b_B , 1/m
2.5580	0.066471	2.6099	0.019748	5.3669	0.14202
2.3391	0.059896	2.6465	0.021283	3.2965	0.062514
3.5328	0.076370	1.7336	0.020290	2.8587	0.053302
3.7970	0.085095	2.2687	0.021759	3.6220	0.077075
2.4405	0.041769	2.2867	0.020602	4.6682	0.14352
2.1881	0.035081	2.4601	0.022276	4.6497	0.14002
2.3882	0.049005	3.0087	0.021673	4.3863	0.13299
2.4580	0.059011	3.1137	0.022520	9.2629	0.30343
2.8347	0.033679	3.0848	0.022428	2.3216	0.017959
2.3648	0.026237	3.0168	0.021980	2.2576	0.018442
2.1734	0.020614	2.9318	0.024618	1.6314	0.018788
2.2631	0.020900	2.6125	0.030094	2.5851	0.028714
2.2297	0.026031	2.4951	0.028691	2.2565	0.020200
2.7781	0.027610	2.1016	0.026573	2.9872	0.039515
1.7422	0.023861	3.5378	0.020215	2.6492	0.026690
1.8224	0.020247	3.3968	0.016528	2.7387	0.020780
1.9048	0.021528	3.7196	0.021640	0.78230	0.0054816
1.8562	0.022812	2.4638	0.026969	0.37960	0.0043522
2.0120	0.022339	1.9339	0.028685	0.43410	0.0040586
2.2978	0.019499	3.7723	0.082937	0.58070	0.0039305

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6. V. I. Mankovsky, and V. I. Haltrin, "Light scattering phase functions measured in waters of Mediterranean Sea,"– Presented to the *OCEANS 2002 MTS-IEEE Conference*, Biloxi, Mississipi, USA, October 29-31, 2002.†

7. V. I. Haltrin, "Theoretical and empirical phase-functions for Monte-Carlo calculations of light scattering in sea water." in: *Proceedings of the Fourth International Conference Remote Sensing for Marine and Coastal Environments: Technology and Applications*, I, Publication by Environmental Research Institute of Michigan, Ann Arbor, Michigan, 509-518 (1997).[Errata: In Eq.(45) *e* should be replaced by *10*].†

9. Our recent spectral measurements in the Gulf of Mexico in 2002 show that the spectral dependence of phase functions is very weak and we can use measurements at 515, 520, and 555 nm together with the resulting error in the range less than 5%.

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